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HD 271791: dynamical versus binary-supernova ejection scenario

V. V. Gvaramadze*

Sternberg Astronomical Institute, Moscow State University, Universitetskij Pr. 13, Moscow 119992, Russia

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ABSTRACT

The atmosphere of the extremely high-velocity ($530 - 920$ km s^{-1}) early B-type star HD 271791 is enriched in α-process elements, which suggests that this star is a former secondary component of a massive tight binary system and that its surface was polluted by the nucleosynthetic products after the primary star exploded in a supernova. It was proposed that the (asymmetric) supernova explosion unbind the system and that the secondary star (HD 271791) was released at its orbital velocity in the direction of Galactic rotation. In this Letter, we show that to explain the Galactic rest-frame velocity of HD 271791 within the framework of the binary-supernova scenario, the stellar remnant of the supernova explosion (a $\lesssim 10$ M$_\odot$ black hole) should receive an unrealistically large kick velocity of $\geqslant 750 - 1200$ km s^{-1}. We therefore consider the binary-supernova scenario as highly unlikely and instead propose that HD 271791 attained its peculiar velocity in the course of a strong dynamical three- or four-body encounter in the dense core of the parent star cluster. Our proposal implies that by the moment of encounter HD 271791 was a member of a massive post-supernova binary.

Key words: Stars: kinematics – stars: individual: HD 271791

1 INTRODUCTION

HD 271791 (also MO 88) is a B2III star (Carozzi 1974) located at a high Galactic latitude of $\simeq 30^\circ$. The large separation of HD 271791 from the Galactic plane and its very high heliocentric radial velocity of $\gtrsim 400$ km s^{-1} (Carozzi 1974; Kilkenny & Muller 1989) suggest that this star is an extremely high-velocity runaway star. Subsequent proper motion measurements showed that HD 271791 originated on the periphery of the Galactic disc (at a galactocentric distance of $\gtrsim 15$ kpc) and that its Galactic rest-frame velocity is $\simeq 530 - 920$ km s^{-1} (Heber et al. 2008). Velocities of this order of magnitude are typical of the so-called hypervelocity stars (HVSs) – the ordinary stars moving with peculiar velocities exceeding the escape velocity of our Galaxy (Brown et al. 2005; Edelmann et al. 2005; Hirsch et al. 2005). The existence of the HVSs was predicted by Hills (1988), who showed that close encounter between a tight binary system and the supermassive black hole (BH) in the Galactic Centre could be responsible for ejection of one of the binary components with a velocity of several 1000 km s^{-1} (see also Yu & Tremaine 2003). It is therefore plausible that some HVSs were produced in that way (Gualandris, Portegies Zwart & Sipior 2005; Baumgardt, Gualandris & Portegies Zwart 2006; Levin 2006; Sesana, Haardt & Madau 2006; Ginsburg & Loeb 2006; Lu, Yu & Lin 2007; Löckmann & Baumgardt 2008). Interestingly, HD 271791 is the only HVS whose birth place was constrained by direct proper motion measurements and the origin of just this star cannot be associated with the Galactic Centre.

An alternative explanation of the origin of HVSs and other high-velocity objects (e.g. the hyperfast neutron stars; see Chatterjee et al. 2005; Hui & Becker 2006) is that they (or their progenitors) attained peculiar velocities in the course of strong dynamical three- or four-body encounters in young and dense star clusters located in the Galactic disc (Gvaramadze 2006a, 2007; Gvaramadze, Gualandris & Portegies Zwart 2008) or in the Large Magellanic Cloud (Gualandris & Portegies Zwart 2007).

Przybilla et al. (2008) found that the atmosphere of HD 271791 is enriched in several α-process elements. To explain this enrichment, they suggested that HD 271791 was a secondary of a massive tight binary and that its surface was polluted by the nucleosynthetic products after the primary star exploded in a supernova (SN). They also suggested that the binary was disrupted by (asymmetric) SN explosion and assumed that HD 271791 was released at its orbital velocity. In this Letter, we show that, to explain the peculiar velocity of HD 271791 within the framework of the binary-SN scenario, the stellar remnant of the SN explosion (a $\lesssim 10$ M$_\odot$ BH, according to Przybilla et al. 2008) should receive an unrealistically large kick velocity of $\geqslant 750 - 1200$ km s^{-1}. We

* E-mail: vgvaram@mx.iki.rssi.ru

therefore consider the binary-SN scenario as highly unlikely and instead propose that HD 271791 attained its extremely high peculiar velocity in the course of a strong dynamical three- or four-body encounter in the dense core of the parent star cluster. Our proposal implies that by the moment of encounter HD 271791 was a member of a massive post-SN binary.

2 HD 271791 AS A FORMER SECONDARY COMPONENT OF A MASSIVE TIGHT BINARY

The spectral analysis of HD 271791 by Przybilla et al. (2008) revealed that the Fe abundance in its atmosphere is subsolar and that the α-process elements are enhanced. The first finding is consistent with the origin of HD 271791 in the metal-poor outskirts of the Galactic disc, while the second one suggests that this star was a secondary component of a massive tight binary (see above). Przybilla et al. (2008) believe that the binary-SN explosion could be responsible not only for the α-enhancement in HD 271791 but also for the extremely high space velocity of this star. Below, we outline their scenario.

The large separation of HD 271791 from the Galactic plane ($\simeq$ 10 kpc) along with the proper motion measurements (Heber et al. 2008) implies that the time-of-flight of this 11 ± 1 $\mathrm{M}_\odot$ star is comparable to its evolutionary lifetime of 25 ± 5 Myr, which in turn implies that the star was ejected within several Myr after its birth in the Galactic disc. The ejection event was connected with disruption of a massive tight binary following the SN explosion. The original binary was composed of a primary star of mass of $\gtrsim 55$ $\mathrm{M}_\odot$ and an early B-type secondary (HD 271791), so that the SN explosion and the binary disruption occurred early in the lifetime of HD 271791. The system was close enough to go through the common-envelope phase before the primary exploded in a SN. During the common-envelope phase, the primary star lost most of its hydrogen envelope and the binary became a tight system composing of a Wolf-Rayet star and an early B-type main-sequence star[1]. At the moment of SN explosion, the mass of the primary star was $\lesssim 20$ $\mathrm{M}_\odot$ and the binary semimajor axis was $\sim 14\,\mathrm{R}_\odot$ (that corresponds to the orbital velocity of the secondary of $\lesssim 420$ $\mathrm{km\,s^{-1}}$). The exploded star expelled $\simeq 10$ $\mathrm{M}_\odot$ of its mass while the remaining mass collapsed to a $\lesssim 10$ $\mathrm{M}_\odot$ BH. The SN explosion was asymmetric enough to disrupt the system. Przybilla et al. (2008) assumed that HD 271791 was released at its orbital velocity and that at the time of binary disruption the vector of the orbital velocity was directed by chance along the Galactic rotation direction. The first assumption is based on the wide-spread erroneous belief that runaways produced from a SN in a binary system have peculiar velocities comparable to their pre-SN orbital velocities. The second assumption is required to explain the difference between the assumed space velocity from the binary disruption and the Galactic rest-frame velocity of HD 271791 (provided that the latter is on the low end of the observed range $530-920$ $\mathrm{km\,s^{-1}}$).

[1] For an alternative channel for the formation of very tight massive binaries see de Mink et al. (2009)

In the next Section, we discuss the conditions under which the secondary star could be launched into free flight at a velocity equal to its pre-SN orbital one.

3 HD 271791: BINARY-SUPERNOVA SCENARIO

One of two basic mechanisms producing runaway stars is based on a SN explosion in a massive tight binary system (Blaauw 1961). (The second one is discussed in Section 4.) After the primary star exploded in a SN, the binary system could be disintegrated if the system lost more than half of its pre-SN mass (Boersma 1961) and/or the SN explosion was asymmetric (so that the stellar remnant, either a neutron star or a BH, received at birth a kick velocity exceeding the escape velocity from the system; Stone 1982; Tauris & Takens 1998).

In the case of binary disruption following the symmetric SN explosion, the stellar remnant is released at its orbital velocity, while the space velocity of the secondary star, $V_{\rm sec}$, is given by (Boersma 1961; Radhakrishnan & Shukre 1985; Tauris & Takens 1998)

$$V_{\rm sec} = \sqrt{1-2\frac{m_1+m_2}{m_1^2}}\,V_{\rm orb}\,, \quad (1)$$

where $m_1 > 2+m_2, m_1 = M_1/M_{\rm co}, m_2 = M_2/M_{\rm co}$, M_1 and M_2 are the pre-SN masses of the primary and the secondary stars, $M_{\rm co}$ is the mass of the compact object formed in the SN explosion, $V_{\rm orb} = [GM_1^2/(M_1+M_2)a]^{1/2}$ is the orbital velocity of the secondary star, G is the gravitational constant and a is the binary semimajor axis. It follows from equation (1) that $V_{\rm sec} \simeq V_{\rm orb} \simeq (GM_1/a)^{1/2}$ if $M_1 >> M_2, M_{\rm co}$.

The above consideration shows that the secondary star could achieve a high peculiar speed if one adopts a large pre-SN mass of the primary (i.e. $M_1 >> M_{\rm co}$). But, the stellar evolutionary models suggest that the pre-SN masses of stars with initial (zero-age main-sequence) masses, $M_{\rm ZAMS}$, from 12 to 120 $\mathrm{M}_\odot$ do not exceed $\sim 10-17$ $\mathrm{M}_\odot$ (Schaller et al. 1992; Vanbeveren, De Loore & Van Rensbergen 1998; Woosley, Heger & Weaver 2002; Meynet & Maeder 2003). Using these figures and assuming that the pre-SN binary is as tight as possible (i.e. the secondary main-sequence star is close to filling its Roche lobe), one can estimate the maximum possible velocity achieved by a runaway star in the process of binary disruption following the symmetric SN explosion. Assuming that the SN explosion left behind a neutron star (i.e. $M_{\rm co} = 1.4$ $\mathrm{M}_\odot$) and adopting $M_1 = 10-17$ $\mathrm{M}_\odot$, one has that a 3 $\mathrm{M}_\odot$ secondary star could attain a peculiar velocity of $\simeq 300-500\,\mathrm{km\,s^{-1}}$, while a 10 $\mathrm{M}_\odot$ star could be ejected with a speed of $\simeq$ 350 $\mathrm{km\,s^{-1}}$.

Note that the pre-SN mass is maximum for stars with $M_{\rm ZAMS} \simeq 20-25$ $\mathrm{M}_\odot$ and $\gtrsim 80$ $\mathrm{M}_\odot$ [see Fig. 6 of Meynet & Maeder (2003)]. In the first case, the SN explosion leave behind a neutron star, while in the second one the stellar SN remnant is a BH of mass $M_{\rm co} \geqslant 5$ $\mathrm{M}_\odot$ (e.g. Woosley et al. 2002; Eldridge & Tout 2004). The large separation of HD 271791 from the Galactic plane implies that this massive star was ejected very soon after its birth in the Galactic disc (see Section 2). From this, it follows that to explain the space velocity of HD 271791 within the framework of the binary-SN scenario one should assume that the primary was

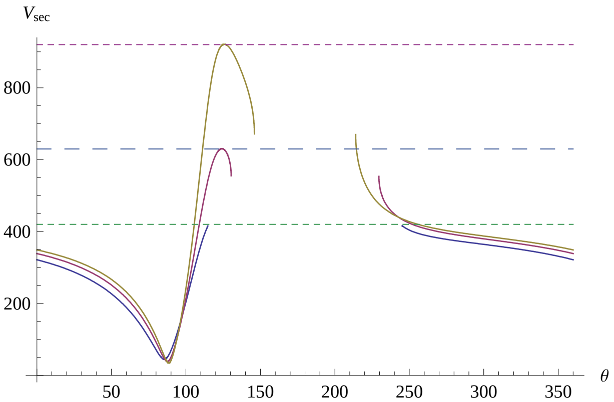

Figure 1. The peculiar velocity of the secondary star (HD 271791) as a function of the angle, θ, between the kick vector and the direction of motion of the exploding star and the magnitude of the kick [750 $\mathrm{km\,s^{-1}}$ (blue line), 1000 $\mathrm{km\,s^{-1}}$ (red line), 1200 $\mathrm{km\,s^{-1}}$ (yellow line)]. The discontinuities in the curves correspond to a range of angles θ for which the system remains bound. The horizontal long-dashed line indicates the Galactic rest-frame velocity of HD 271791 of 630 $\mathrm{km\,s^{-1}}$, corresponding to the "best" proper motion given in Heber et al. (2008). The horizontal short-dashed lines indicate the orbital velocity of HD 271791 of 420 $\mathrm{km\,s^{-1}}$ [suggested by the scenario of Przybilla et al. (2008)] and the maximum possible Galactic rest-frame velocity of HD 271791 of 920 $\mathrm{km\,s^{-1}}$ (Heber et al. 2008). See text for details.

a short-lived very massive star (Przybilla et al. 2008). In this case, the stellar SN remnant is a BH and the SN ejecta is not massive enough to cause the disruption of the binary system.

According to Przybilla et al. (2008), the pre-SN mass of the primary star was $\lesssim 20\ \mathrm{M}_\odot$ (i.e. somewhat larger than the maximum mass predicted by the stellar evolutionary models; see above) and the SN explosion left behind a BH of mass $\lesssim 10\ \mathrm{M}_\odot$ (comparable to the mass of the secondary star, HD 271791), i.e. the system lost less than a half of its mass. Thus, to disrupt the binary, the SN explosion should be asymmetric. In this case, the space velocities of the BH and HD 271791 depend on the magnitude and the direction of the kick imparted to the BH at birth (Tauris & Takens 1998). To estimate $V_{\rm sec}$, one can use equations (44)-(47) and (54)-(56) given in Tauris & Takens (1998). It follows from these equations that $V_{\rm sec}$ is maximum if the vector of the kick velocity does not strongly deviate from the orbital plane of the binary and is directed nearly towards the secondary, i.e. the angle, θ, between the kick vector and the direction of motion of the exploding star is $\sim \theta_* = \arccos(-v/w)$, where $v = [G(M_1 + M_2)/a]^{1/2}$ is the relative orbital velocity and w is the kick velocity (see Gvaramadze 2006b).

Fig. 1 shows how the direction and the magnitude of the kick affect $V_{\rm sec}$. The three solid lines represent $V_{\rm sec}$ calculated for the binary parameters suggested by Przybilla et al. (2008) and three kick magnitudes of 750 $\mathrm{km\,s^{-1}}$ (blue line), 1000 $\mathrm{km\,s^{-1}}$ (red line) and 1200 $\mathrm{km\,s^{-1}}$ (yellow line). One can see that to launch HD 271791 at its pre-SN orbital velocity $V_{\rm orb} \simeq 420\ \mathrm{km\,s^{-1}}$ the kick imparted to the BH should be at least as large as 750 $\mathrm{km\,s^{-1}}$. In fact, the kick magnitude should be much larger since for kicks $\simeq 750\ \mathrm{km\,s^{-1}}$ the kick direction must be carefully tuned (see Fig 1), i.e. θ should be either $\simeq 115^\circ$ or $\simeq 245^\circ$ (note that for $115^\circ \lesssim \theta \lesssim 245^\circ$ the binary system remains bound). The even larger kicks of $\geqslant 1000$ and $\geqslant 1200\ \mathrm{km\,s^{-1}}$ are required to explain the Galactic rest-frame velocities of HD 271791 of 630 and 920 $\mathrm{km\,s^{-1}}$ [corresponding, respectively, to the "best" and the maximum proper motions given in Heber et al. (2008); see also Przybilla et al. (2008)]. Although one cannot exclude a possibility that BHs attain a kick at birth, we note that there is no evidence that the kick magnitude could be as large as required by the above considerations (see Nelemans et al. 1999; Fryer & Kalogera 2001; Gualandris et al. 2005).

Thus, we found that to explain the peculiar velocity of HD 271791 the magnitude of the kick attained by the $\lesssim 10\ \mathrm{M}_\odot$ BH should be unrealistically large ($\geqslant 750 - 1200\ \mathrm{km\,s^{-1}}$)[2], that makes the binary-SN ejection scenario highly unlikely (cf. Gvaramadze 2007; Gvaramadze & Bomans 2008).

4 HD 271791: DYNAMICAL EJECTION SCENARIO

The second basic mechanism responsible for the origin of runaway stars is based on dynamical three- or four-body interactions in dense stellar systems (Poveda et al. 1967; van Albada 1968; Aarseth 1974; Gies & Bolton 1986). Below, we discuss three possible channels for producing high-velocity runaways within the framework of the dynamical ejection scenario.

The first possibility is that the high-velocity stars are the product of breakup of unstable close triple systems (Szebehely 1979; Anosova, Colin & Kiseleva 1996), e.g. hierarchical triple stars with the ratio of the semimajor axes of the outer and the inner binaries $a_{\rm out}/a_{\rm in} \lesssim 3-4$ (Kiseleva, Eggleton & Anosova 1994; Mardling & Aarseth 2001). Such systems are dissociated within several tens of crossing times and leave behind a more tightly bound binary and a single (usually the least massive) star, escaping with a velocity $V_{\rm esc} \sim (|E_0|/m)^{1/2}$, where $|E_0| \propto M^2/R$ is the total energy of the system with mass $M = m_1 + m_2 + m_3$ and scalelength $R (\sim a_{\rm in})$, and $m_3 (< m_1, m_2)$ is the mass of the ejected star (Valtonen & Mikkola 1991; Sterzik & Durisen 1995). For a triple star consisting of the inner binary with main-sequence components with mass $m_1 = m_2 = 50\ \mathrm{M}_\odot$ and $a_{\rm in} \simeq 40\,\mathrm{R}_\odot$ (i.e. the binary components are close to filling their Roche lobes) and the third star with mass $m_3 = 10\ \mathrm{M}_\odot$, the ejection speed of the latter star could be $\sim 800\ \mathrm{km\,s^{-1}}$.

To reconcile this ejection scenario with the presence of nucleosynthetic products in the atmosphere of HD 271791, one should assume that (i) the unstable triple star was formed due to the close encounter between two (massive) binaries (e.g. Mikkola 1983), (ii) HD 271791 was a secondary component of one of these binaries, and (iii) by the moment of the encounter, the binary containing HD 271791 has experienced SN explosion and remained bound [i.e. the stellar supernova remnant (BH) received a small or no kick at birth]. The requirement that HD 271791 was a member of a

[2] Note that the smaller the mass of the BH the larger the kick is required to accelerate the secondary to a given velocity.

post-SN binary should also be fulfilled in two other dynamical processes discussed below.

The second possibility is that the high-velocity runaways originate through the interaction between two massive hard (Hills 1975; Heggie 1975) binaries (Mikkola 1983; Leonard & Duncan 1990). The runaways produced in binary-binary encounters are frequently ejected at velocities comparable to the orbital velocities of the binary components (e.g. Leonard & Duncan 1990) and occasionally they can attain a velocity as high as the escape velocity, $V_{\rm esc} = (2GM_*/R_*)^{-1/2}$, from the surface of the most massive star in the binaries (Leonard 1991). For the upper main-sequence stars with the mass-radius relationship (Habets & Heintze 1981), $R_* = 0.8(M_*/\,{\rm M}_\odot)^{0.7}\,{\rm R}_\odot$, where R_* and M_* are the stellar radius and the mass, one has $V_{\rm esc} \simeq 700 \ {\rm km\,s}^{-1}(M_*/\,{\rm M}_\odot)^{0.15}$ (e.g. Gvaramadze 2007), so that the ejection velocity could in principle be as large as $\simeq 1100 - 1200 \ {\rm km\,s}^{-1}$ if the binaries contain at least one star of mass of $20 - 40 \ {\rm M}_\odot$. Numerical scattering experiments performed by Leonard (1991) showed that about 4 per cent of runaways produced by binary-binary interactions have velocities of $\simeq 0.5V_{\rm esc}$ (i.e. $\simeq 550 - 600 \ {\rm km\,s}^{-1}$), which is enough to explain the Galactic rest-frame velocity of HD 271791.

The third possibility is that the high-velocity runaway stars attain their peculiar velocities in the course of close encounters between massive hard binaries and a very massive star (Gvaramadze 2007), formed through runaway collisions of ordinary massive stars in dense star clusters (Portegies Zwart et al. 1999; Portegies Zwart & McMillan 2002; Gürkan et al. 2004). An essential condition for the formation of very massive stars is that the runaway process should start before the most massive stars in the cluster end their lifetimes (e.g. Gürkan et al. 2004), i.e. the time-scale for core collapse in the cluster (e.g. Gvaramadze et al. 2008),

$$t_{\rm cc} \simeq 3\,{\rm Myr} \left(\frac{M_{\rm cl}}{10^4 \ {\rm M}_\odot}\right)^{1/2} \left(\frac{r_{\rm h}}{1\,{\rm pc}}\right)^{3/2} \left(\frac{\langle m\rangle}{{\rm M}_\odot}\right)^{-1} \times \left(\frac{\ln\Lambda}{10}\right)^{-1} ,$$

where $M_{\rm cl}$ and $r_{\rm h}$ are the total mass and the characteristic (half-mass) radius of the cluster, $\langle m\rangle$ is the mean stellar mass and $\ln\Lambda \simeq 10$ is the Coulomb logarithm, should be less than $\simeq 3 - 4$ Myr. Observations show that the majority of star clusters are very compact ($r_{\rm h} < 1$ pc) at birth (e.g. Kroupa & Boily 2002) so that it is conceivable that an appreciable fraction of them evolves through a collisional stage and form very massive stars. Simple estimates show that our Galaxy can currently host about 100 star clusters with a mass $M_{\rm cl} \geqslant 10^4 \ {\rm M}_\odot$ (Gvaramadze et al. 2008). All these clusters can potentially produce very massive stars and thereby contribute to the origin of high-velocity runaway stars.

A close encounter with the very massive star results in a tidal breakup of the binary[3], after which one of the binary components becomes bound to the very massive star while the second one recoils with a high velocity, given by (Hills 1988; Yu & Tremaine 2003):

$$V_\infty \simeq 500 \ {\rm km\,s}^{-1} \left(\frac{M_{\rm VMS}}{100 \ {\rm M}_\odot}\right)^{1/6} \left(\frac{a'}{30 \ {\rm R}_\odot}\right)^{-1/2} \times \left(\frac{M_1}{10 \ {\rm M}_\odot}\right)^{1/3} , \qquad (2)$$

where $M_{\rm VMS}$ is the mass of the very massive star and a' is the post-SN binary semimajor axis. It follows from equation (2) that, to explain the peculiar velocity of HD 271791 of $\simeq 400 - 600 \ {\rm km\,s}^{-1}$, the mass of the very massive star should be $\gtrsim 100 - 300 \ {\rm M}_\odot$ [the first figure corresponds to the mass of the most massive star formed in a 'normal' way in a cluster with a mass $M_{\rm cl} \simeq 10^4 \ {\rm M}_\odot$ (Weidner & Kroupa 2006)]. Note that the weak dependence of V_∞ on $M_{\rm VMS}$ implies that the velocities of $\simeq 400 \ {\rm km\,s}^{-1}$ can in principle be produced by three-body encounters with ordinary massive stars of mass of $\simeq 40 \ {\rm M}_\odot$. The above estimates can be supported by the results of three-body scattering experiments which showed that $\gtrsim 3$ per cent of encounters between hard massive binaries and a very massive star of mass of $200 - 300 \ {\rm M}_\odot$ produce runaways with $V_\infty \geqslant 500 - 600 \ {\rm km\,s}^{-1}$ (Gvaramadze, Gualandris & Portegies Zwart 2009).

Note also that the requirement that HD 271791 was a member of a post-SN binary does not contradict to our proposal that this star can attain its high speed via a three-body encounter with a very massive star (i.e. with the star more massive than the primary star in the original binary). The merging of ordinary stars results in effective rejuvenation of the collision product (e.g. Meurs & van den Heuvel 1989) so that the very massive star could still be on the main sequence when the most massive ordinary stars start to explode as SNe (e.g. Portegiez Zwart et al. 1999).

5 SUMMARY

We have discussed the origin of the extremely high-velocity early B-type star HD 271791 within the framework of the binary-supernova and the dynamical ejection scenarios. A common feature in these competing scenarios for producing runaway stars is that HD 271791 was a secondary of a tight massive binary and that its surface was enriched in α-process elements after the primary star exploded in a supernova. Przybilla et al. (2008) favoured the binary-supernova scenario and suggested that HD 271791 attained its high speed due to the disintegration of the binary caused by the asymmetric supernova explosion. We showed, however, that to explain the space velocity of HD 271791 within the framework of this scenario the kick velocity received by the stellar supernova remnant (a $\sim 10 \ {\rm M}_\odot$ black hole) should be extremely large, $\geqslant 750 - 1200 \ {\rm km\,s}^{-1}$. Since there is no evidence that black holes can attain kicks of this magnitude, we consider the binary-supernova scenario for the origin of HD 271791 as highly unlikely. Instead, we proposed that the post-supernova binary remained bound and that the high

[3] Note that most of mass of very massive stars is concentrated in a dense and compact core. According to Yungelson et al. (2008; also Yungelson, personal communication), the 99 per cent of mass of a 500 ${\rm M}_\odot$ star is confined within a sphere of radius of $\sim 30 \ {\rm R}_\odot$, so that in the process of tree-body encounter with a binary the very massive star could be considered as a point mass (cf. Gvaramadze 2007).

speed of HD 271791 is due to a strong dynamical encounter between this binary and another massive binary or a very massive star (formed via runaway merging of ordinary stars in the core of the parent star cluster). We argue that similar dynamical processes could also be responsible for the origin of other hypervelocity stars and therefore expect that the future proper motion measurements for these objects will show that some of them were expelled from the Galactic disc.

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